

# Effect of meson cloud on the jet nuclear modification factor in $pA$ collisions

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We study the effect of the nucleon meson cloud on centrality dependence of the jet nuclear modification factor  $R_{pA}$ . We find that the meson-baryon Fock components may lead to a noticeable deviation of  $R_{pA}$  from unity. Our results for  $R_{pA}$  show the same tendency as that observed by ATLAS in  $p + Pb$  collisions at  $\sqrt{s} = 5.02$  TeV. The meson cloud suppresses the central jet events and enhances the peripheral jet events. But quantitatively the effect is somewhat smaller than in the data.

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## I. INTRODUCTION

Factorization of hard and soft process [1] suggests that in the cross section of hard reactions the soft physics can be accumulated in parton distribution functions (PDFs) of colliding particles. However, the factorization theorems do not forbid the existence of correlations between hard and soft final particles. The correlations of this type have been observed in recent measurements by ATLAS [2] of the centrality dependence of the jet nuclear modification factor  $R_{pA}$  for  $p + Pb$  collisions at  $\sqrt{s} = 5.02$  TeV. The  $R_{pA}$  for jet production is defined as

$$R_{pA} = \frac{dN_{pA}^{jet}/dp_T dy}{N_{coll} dN_{pp}^{jet}/dp_T dy}, \quad (1)$$

where  $N_{pA}^{jet}$  and  $N_{pp}^{jet}$  are the jet yields in  $pA$  and  $pp$  collisions, and  $N_{coll}$  is the number of the binary collisions. In [2] it has been observed that the jet nuclear modification factor  $R_{pPb}$  in the broad (minimum bias) 0 – 90% centrality region is close to unity. However, it is not the case for narrow centrality bins. For high  $p_T$  the  $R_{pPb}$  has been found to be suppressed in central events ( $R_{pPb} < 1$ ) and to be enhanced in peripheral events ( $R_{pPb} > 1$ ). The effect is more pronounced for the proton-going rapidities ( $y > 0$ ). In principle the suppression of the jet  $R_{pPb}$  in the central events might arise from the final state interaction effects in the small-size quark-gluon plasma, if it is formed in  $pPb$  collisions [3]. However, the fact the minimum bias jet  $R_{pPb}$  observed in [2] is approximately consistent with unity, says that the potential effect of the plasma mini-fireball is small (or it is well compensated by the medium effects in  $pp$  collisions [4] due to modification of the denominator of (1) [3]). In [5] it was proposed that the ATLAS data [2] can be explained by the initial state correlations of the hard and soft partons in the wave function of the projectile proton. The mechanism of [5] assumes that in the presence of an energetic parton (which is necessary for a hard process to occur) the number of soft partons in the projectile is suppressed. Then, assuming that the multiplicity of soft particles produced in the underlying events (UEs) with jet production is proportional to the number of soft partons in the projectile proton, it leads naturally to correlation of the jet  $R_{pA}$  with the multiplicity/centrality of the UEs. In the recent more sophisticated analyses [6, 7] this parton level mechanism has been addressed within the Monte-Carlo generators PYTHIA and HIJING. But only a very crude agreement with the ATLAS data [2] has been attained. However, of course, similarly to [5], the analyses [6, 7] are of a qualitative nature. Because, due to the nonperturbative physics of the UE, it impossible to obtain robust predictions for the multiplicity/centrality dependence of  $R_{pA}$  within the parton level schemes.

The purpose of the present work is to study the effect of the meson-baryon Fock components in the proton on the jet nuclear modification factor. It is known that the total weight of the meson-baryon Fock states in the fast physical nucleon may be as large as  $\sim 40\%$  [8]. The meson cloud of the proton plays an important role in the flavor dependence of nucleon PDFs in deep inelastic scattering (DIS), and is probably responsible for the violation of the Gottfried sum rule [8]. The emergence of the centrality dependence of  $R_{pA}$  in the scenario with the meson cloud is conceptually very similar to the partonic mechanism of [5]. In this scenario the hard process selects in the projectile proton wave function fluctuations with a reduced fraction of the meson-baryon states (as compared to the soft interactions). It results in suppression of the UE multiplicity in jet production at high  $p_T$ , that should lead to centrality dependence of  $R_{pA}$  due to difference in the centrality categorization for minimum bias (soft) events and jet events. In the present analysis we simulate the UE activity in jet events within the Monte-Carlo Glauber (MCG) wounded nucleon model with the meson cloud developed in [9, 10]. We find that a considerable part of the centrality dependence of the jet nuclear modification factor measured by ATLAS [2] may be explained by the meson-baryon Fock components of the proton.

## II. THEORETICAL FRAMEWORK

Our treatment of the meson-baryon components is similar to that in previous analyses of the meson cloud effects in DIS based on the infinite momentum frame (IMF) picture [8, 11–13]. In this picture the physical nucleon IMF wave function reads

$$|N_{phys}\rangle = \sqrt{W_N}|N\rangle + \sum_{MB} \int dx d\mathbf{k} \Psi_{MB}(x, \mathbf{k}) |MB\rangle, \quad (2)$$

where  $N$ ,  $B$ , and  $M$  denote the bare baryon and meson states,  $x$  is the meson fractional longitudinal momentum,  $\mathbf{k}$  is the transverse meson momentum,  $\Psi_{MB}$  is the  $MB$  probability amplitude,  $W_N = 1 - W_{MB}$  is the weight of the one-body Fock state in the physical nucleon, and

$$W_{MB} = \sum_{MB} \int dx d\mathbf{k} |\Psi_{MB}(x, \mathbf{k})|^2 \quad (3)$$

is the total weight of the  $MB$  Fock components. The proton PDF for a parton  $i$ ,  $D_{i/p}$ , corresponding to the Fock state decomposition (2), can be written as [8]

$$D_{i/p}(x, Q^2) = W_N \tilde{D}_{i/p}(x, Q^2) + \int_x^1 \frac{dy}{y} \tilde{D}_{i/M}(x/y, Q^2) f_{M/p}(y) + \int_x^1 \frac{dy}{y} \tilde{D}_{i/B}(x/y, Q^2) f_{B/p}(y). \quad (4)$$

Here  $\tilde{D}_{i/M}$  and  $\tilde{D}_{i/B}$  are the PDFs for the bare particles, and  $f_{M,B/p}$  are the  $p \rightarrow M, B$  splitting functions given by

$$f_{M/N}(x) = \int d\mathbf{k} |\Psi_{MB}(x, \mathbf{k})|^2, \quad (5)$$

$$f_{B/N}(x) = \int d\mathbf{k} |\Psi_{MB}(1-x, \mathbf{k})|^2. \quad (6)$$

The analyses of the meson effects in DIS [8, 11–13] show that in the Fock state decomposition (2) it is enough to include  $\pi N$ ,  $\pi\Delta$ ,  $\rho N$  and  $\rho\Delta$  two-body systems. The total weight of these states in the physical nucleon is about 40% [8] with the dominating contribution from the  $\pi N$  states. For simplicity, we neglect the difference in the PDFs generated by the above four two-body states, and treat them as one effective  $\pi N$  state with normalization  $W_{MB} = 0.4$ . This is a reasonable assumption, because the  $\Delta$  and  $\rho$  PDFs should be close to that for  $N$  and  $\pi$ . Following the analyses of DIS [8, 13] we evaluated the  $f_{\pi/p}$  splitting function using the ordinary  $\gamma_5$  pion-nucleon vertex with the dipole formfactor

$$F = \left( \frac{\Lambda^2 + m_N^2}{\Lambda^2 + M_{\pi N}^2(x, \mathbf{k})} \right)^2 \quad (7)$$

with  $\Lambda = 1.3$  GeV (see [10] for details),  $M_{\pi N}$  is the invariant mass of the  $\pi N$  state in the IMF.

We write the jet cross section ( $\sigma(p_T, y) = d\sigma/dp_T dy$ ) as a sum

$$\sigma(p_T, y) = \sigma_N(p_T, y) + \sigma_{MB}(p_T, y), \quad (8)$$

where the first term on the right-hand-side of (8) corresponds to the one-body contribution to the proton PDFs from the first term in (4), and the second term describes the effect from the last two terms in (4) due to the two-body Fock components. In jet events the dynamics of the UEs in  $pA$  collisions depends crucially on the relative contribution of the  $\sigma_N$  and  $\sigma_{MB}$  to the total jet cross section, because it controls the probabilities of the  $N$  and  $MB$  states in the hard process given by

$$W_N^j(p_T, y) = \frac{\sigma_N(p_T, y)}{\sigma_N(p_T, y) + \sigma_{MB}(p_T, y)}, \quad (9)$$

$$W_{MB}^j(p_T, y) = \frac{\sigma_{MB}(p_T, y)}{\sigma_N(p_T, y) + \sigma_{MB}(p_T, y)}. \quad (10)$$

In our model in jet events soft interaction of the projectile proton and the nucleus with the probability  $W_N^j$  occurs as  $N + A$  collision and with the probability  $W_{MB}^j$  as  $MB + A$  collision.

As usual, we define the minimum bias centrality  $c$  through the theoretical charged multiplicity distribution  $P$  [14]

$$c(N_{ch}) = \sum_{N=N_{ch}}^{\infty} P(N). \quad (11)$$

Here  $N_{ch}$  is the theoretical charged multiplicity in the pseudorapidity window used for the centrality categorization (as in [9, 10] we use the pseudorapidity region  $|\eta| < 0.5$ ). It is important that the number of the binary collisions in the denominator of (1) is defined in terms of the centrality classes for the minimum bias events. The centrality dependence of  $R_{pA}$  arises due to the fact that the shapes of the charged multiplicity distributions for the minimum bias soft events (used in the centrality selection) and for the jet events are different. For a given centrality class  $\{c\}$   $N_{coll}$  can be written as [15]

$$N_{coll}(\{c\}) = \frac{\sigma_{in}^{NN}}{\sigma_{in}^{pA}} \int d\mathbf{b} T(b) P_s(\{c\}, b), \quad (12)$$

where  $P_s$  is the probability that multiplicity of the UE belongs to the centrality class  $\{c\}$  and  $T$  is the impact parameter probability distribution of the binary collisions. In the approximation of zero interaction radius  $T$  is reduced to the nuclear profile function  $T_A(\mathbf{b}) = \int dz \rho_A(\mathbf{b}, z)$  ( $\rho_A$  is the nuclear density). In our two-component model  $P_s$  can be written as

$$P_s(\{c\}, b) = W_N P_N(\{c\}, b) + W_{MB} P_{MB}(\{c\}, b), \quad (13)$$

where  $P_{N,MB}(\{c\}, b)$  are the centrality probabilities for the  $N + A$  and  $MB + A$  collisions. In calculation of the numerator of (1) the probability that in a jet event the multiplicity for the UE belongs to the centrality class  $\{c\}$  (we denote it  $P_j$ ) can be written via  $W_N^j$  and  $W_{MB}^j$  as

$$P_j(\{c\}, b, p_T, y) = W_N^j(p_T, y) P_N(\{c\}, b) + W_{MB}^j(p_T, y) P_{MB}(\{c\}, b). \quad (14)$$

In terms of the probabilities (13), (14) the theoretical  $R_{pA}$  can be written as

$$R_{pA}(\{c\}, p_T, y) = \frac{R(p_T, y) \int d\mathbf{b} T(b) P_j(\{c\}, b, p_T, y)}{\int d\mathbf{b} T(b) P_s(\{c\}, b)}. \quad (15)$$

Here the factor  $R$  account for modification of the hard cross section due to the nuclear modification of the PDFs of bound nucleons (in nucleus). For the whole centrality range  $\{c\} = (0, 1)$   $P_{j,s} = 1$  and  $R_{pA}$  is simply reduced to  $R$ .

### III. NUMERICAL RESULTS AND DISCUSSION

In Fig. 1 we show  $f_{M/p}$  splitting function used in (4) obtained with  $\gamma_5$  pion-nucleon vertex for the dipole formfactor (7). One can see that the meson spectrum is strongly peaked near  $x \sim 0.3$ . For the bare meson PDFs in (4) we use the LO parametrization of the pion PDFs of [17]. For the bare nucleon PDFs we use the LO CTEQ6 [16] parametrizations. For the PDF momentum scale  $Q$  for pion we use the hard parton transverse momentum  $p_T$ . In our model, due to the presence of the  $MB$  component, the transverse mean-square radius of the bare proton becomes smaller by a factor of  $a \approx 0.88$ . To account for a possible decrease of the range of the DGLAP evolution due to a bigger initial momentum scale we take  $Q = ap_T$  for the bare nucleon PDFs. However, the choice  $Q = p_T$  gives practically same results. For the nucleons in a lead nucleus we use the LO CTEQ6 [16] PDFs with the EKS98 [18] nuclear corrections. The hard cross sections have been calculated using the LO pQCD formula. To simulate the higher order effects for the virtuality scale in  $\alpha_s$  we take the value  $cQ$  with  $c = 0.265$  as in the PYTHIA event generator [19]. This gives a fairly good description of the  $p_T$ -dependence of the inclusive jet cross section obtained in [2].

We have computed the numerator and denominator of (15) by sampling  $pA$  collisions within the MCG model with meson cloud developed in [9, 10]. The interested reader is referred to those papers for details of our MCG scheme. In Fig. 2 we compare our results with the ATLAS data [2]. To illustrate the effect of the nuclear modification of the nucleon PDFs, in Fig. 2 we present the results obtained with and without the EKS98 correction factor  $R$  in (15). From Fig. 2 one sees that the effect of the meson cloud on the  $R_{pA}$  shows qualitatively the same tendency as that observed by ATLAS [2]. The  $MB$  component suppresses the central jet events and enhances the peripheral jet

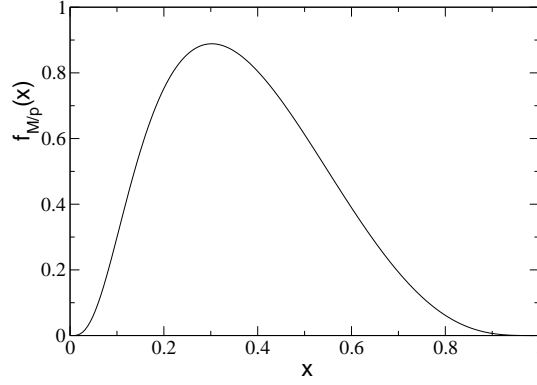


FIG. 1:  $f_{M/p}$  splitting function normalized to  $W_{MB} = 0.4$  obtained using the  $x$ -distribution for the  $\pi N$  Fock component.

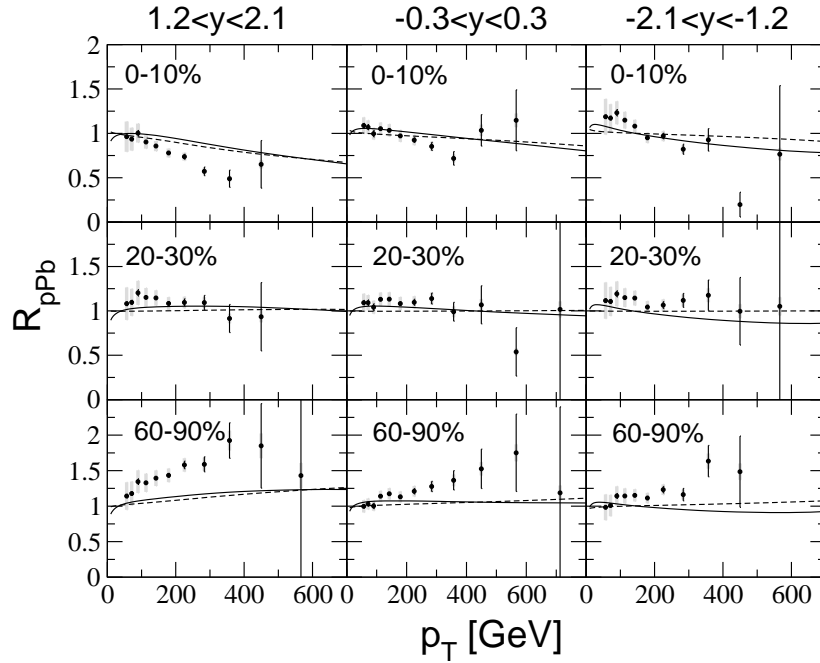


FIG. 2:  $R_{pPb}$  versus  $p_T$  for  $p + Pb$  collisions at  $\sqrt{s} = 5.02$  TeV for 0-10% (upper), 20-30% (middle), 60 – 90% (lower) centrality classes. The solid curves show our results with the EKS98 correction factor  $R$  in (15), and the dashed ones without  $R$ . Data points are from ATLAS [2].

events. Similarly to the ATLAS data the effect is more pronounced at  $y > 0$ . However, quantitatively the effect is somewhat smaller than in the data. It is possible that a better agreement with the ATLAS data [2] can be obtained by accounting for the correlations between hard and soft partons in the bare constituents in the projectile proton, due to the mechanism discussed in [5–7]. We postpone this for future work. Also, it is possible that the meson effects in the proton PDFs can be enhanced due to the nonperturbative quark-gluon-pion anomalous chromomagnetic interaction related to the instantons discussed recently in [20].

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